Materials Science & Engineering A 679 (2017) 379–390

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Effects of cryogenic temperature and pre-stretching on mechanical properties and deformation characteristics of a peak-aged AA6082 extrusion

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ARTICLE INFO

Keywords:
AA6082 alloy
Cryogenic temperature
Mechanical properties
Pre-stretching
Homogenous deformation
Slip localization

ABSTRACT

Plastic deformation studies of a peak-aged AA6082 alloy by means of tensile tests at 77 K and 295 K, and related microstructure characteristics obtained by Scanning Electron Microscopy (SEM), Electron Backscatter Diffraction (EBSD), Transmission Electron Microscopy (TEM) and Atom Force Microscopy (AFM), revealed new results. A simultaneous improvement in ductility and strength occurred at 77 K, but not at 295 K. A higher work hardening accompanied by a more homogeneous slip mode explained the improved properties at 77 K. Pre-stretching at these two temperatures and subsequent tensile testing at room temperature revealed a marked yield point. However, pre-stretching at 77 K exhibited a slightly higher room temperature yield strength and ductility than the condition pre-stretched at 295 K. Annealing after pre-stretching improved ductility and reduced the magnitude of the yield point. Pre-stretching at 77 K and subsequent annealing introduced somewhat higher strength and ductility as compared to the counterpart pre-stretched at 295 K. The observed mechanical behaviour and associated phenomena were directly linked to microstructure characteristics such as deformation substructure history, slip localization, dislocation density and the precipitate $\beta^{'}/\beta^{''}$ ratio.

1. Introduction

Due to attractive mechanical properties such as moderate to high strength, good weld ability and high corrosion resistance, aluminium 6000 series alloys play an important role in light weight structural applications. In the field of industrial applications, two-thirds of extruded products are made of aluminium and 90% of the extrusions are made from 6000 series alloys [1]. Among these, the AA6082 alloy is one of the most widely used [2–4]. Such materials can be heat treated to achieve various degrees of precipitation. The peak ageing treatment involves solution heat treatment to obtain a supersaturated α solid solution and subsequent artificial ageing to accelerate precipitation hardening. Hence, this is a common method for increasing the strength to the maximum level [5]. More specifically, the strength is determined by the volume fraction of precipitates, their structure and in particular the degree of coherency with the Al matrix [6]. So far, accurate relationships between plastic deformation behaviour, process parameters and chemical alloying elements have been presented in many excellent works, which demonstrated intrinsic features of these alloys and their industrial applications [7–9]. However, there are still needs for extending the knowledge of 6000 series aluminium alloys. Detailed relationships among mechanical properties, deformation behaviour, microstructure, processing parameters as well as working conditions are of particular importance.

For structural materials, mechanical properties of materials are among the most important physical properties that determine the range of possible applications. It is well accepted that mechanical properties are highly dependent on the composition, phase structures, crystal defects, and especially, temperature. It was reported that aluminium alloy had desirable or unusual properties at cryogenic temperatures, which made them attractive to cryogenic engineering such as liquefied natural gas (LNG) tanks [10]. In the last decades, numerous research works explored the cryogenic temperature - mechanical properties - microstructure evolution relationships of pure aluminium and its alloys. For example, measurements of dislocation density in relatively pure alloys at 4.2 K revealed that failure upon loading of these materials occurred when the local dislocation density approaches the critical value for spontaneous annihilation [11]. In a study of Al-xLi alloys, the authors observed that the dispersion characteristics of particles were linked to plastic deformation mechanisms at low temperatures spanning from 40 K to 170 K [12]. In pure aluminium deformed at low temperature, the stored dislocation density

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http://dx.doi.org/10.1016/j.msea.2016.10.049
Received 22 June 2016; Received in revised form 14 October 2016; Accepted 15 October 2016
Available online 17 October 2016

increased due to a reduction in dynamic recovery [13]. These obtained microstructures in turn, facilitated a good combination of high strength and ductility. In parallel to the improved mechanical properties, a weaker crystallographic texture was found after deformation at low-than at elevated temperature as exemplified by an AA5754 alloy deformed to a fix strain [14]. In other words, the magnitude of grain rotations reduced when deforming at lower temperatures. Such studies indicate that design of new test procedures and methodologies for aluminium alloys at cryogenic temperature are becoming more and more interesting, since this is a necessary access to the physical essence of material with respect to influence of deformation temperature.

In addition to changes in mechanical properties and texture evolution at cryogenic temperatures, the deformation induced surface roughness might develop otherwise than at room temperature [15]. Generally, the deformation mechanisms that generate surface roughening are governed by the following three principal reasons [16]: (1) the surface grains deform more easily because they are less constrained than interior grains; (2) the free surface allows formation of surface reliefs; (3) on the free surface, strain concentration around a defect is severe. As a result, the surface roughening behaviour becomes an essential factor that determines both the appearance quality of the material and the suitability for a given application [17]. Basic studies relating surface roughness to metallurgical factors for a particular alloy are necessary for a better prediction of the surface appearance, strength, ductility, etc. In our previous work on a fully recrystallized AA6060 alloy (T6) subjected to tensile deformation at 77 K and 295 K, it was observed that slip homogeneity at the former temperature introduced more surface topography than at 295 K [18]. The AA6060 alloy is fundamentally different from the present AA6082 alloy having a fibrous grain structure. The recrystallized AA6060 alloy should be considered a fully constrained crystal plasticity system while the present AA6082 alloy was best described as a relaxed constrained system [19]. According to the author's knowledge, studies on the deformation mechanisms operating at cryogenic temperatures for AA6082 alloy are lacking. Therefore, the present work comprehends systematic studies on the plastic deformation characteristics of an AA6082 alloy deformed at 77 K and 295 K, respectively. One will determine mechanical properties and simultaneously identify processes that control plastic flow, strain hardening behaviour and deformed surface characteristics at these temperatures. Furthermore, a yield drop phenomenon introduced by pre-stretching at 77 K and 295 K reveals new insights into plastic deformation. Hence, the present work provides new information on the cryogenic behaviour of this type of 6000 alloys, having a fibrous microstructure.

2. Experimental procedures

The material used in this investigation was an AA6082 alloy supplied by Hydro Aluminium and having the chemical composition (in wt%): 1.005Si, 0.165Fe, 0.497Mn, 0.687Mg, 0.01Zn, and Al balance. The as-received material was in the form of a flat extrusion, i.e. having 80 mm width and 10 mm thickness. A subsequent heat treatment conducted at 185 °C for 6 h put the billet into peak-aged condition (T6 temper, hardness 115 VHN). This treatment was conducted since the peak-aged state normally is the most strain localizing condition. The intension of this work was to study the effect of pre-stretching at 77 K and 295 K, e.g. with regard to strain localization. Rectangular tensile specimens having 2 mm thickness were machined from the plate mid-section of the T6-aged material, e.g. with the tensile axis being parallel to the extrusion direction (ED) and the specimen width in the normal direction (ND), as shown in Fig. 1. The gauge section of these specimens was 32 mm and 6 mm, i.e. in length and width respectively. For EBSD observation, specimen preparation consisted of mechanical grinding and electro-polishing. Firstly, the specimens were grinded on water cooled silicon carbide papers, followed by mechanical polishing through 6–1 μm. Secondly,

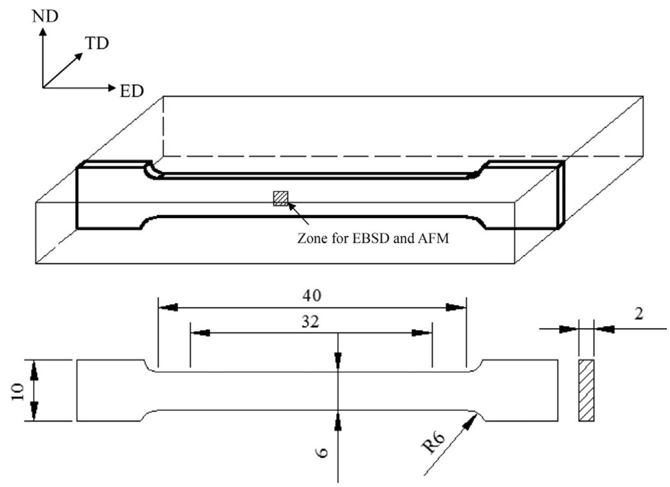

Fig. 1. Schematic illustration of the tensile specimen sampling position, actual inspection plane for SEM-EBSD and AFM analysis and dimensions of the tensile test sample [mm].

electro-polishing was performed in a solution of 80% C2H5OH +20% HCLO4, using a voltage of 20 V for 15 s under a controlled temperature of −30 °C. After electro-polishing, the specimens were cleaned with methanol and dried by a blower. This removed the deformed surface layer after machining. Tensile tests were conducted at both 77 K and 295 K in a universal servo-hydraulic test machine (MTS880) and the initial strain rate was 10^{-4} s^{-1}. This involved three specimens for each test temperature. For deformation at 77 K, the specimens and grips stayed in liquid nitrogen for 15 min before the test started. In the present work, higher test temperatures were not applied in order to exclude other effects such as thermal-assisted deformation, dislocation recovery and evolution of precipitates, etc.

In addition to the peak-aged specimens tensioned to fracture directly, six specimens were pre-strained to 10% at 295 K and six specimens were pre-strained to 10% at 77 K. Then three samples from each pre-straining temperature were stored at room temperature for five days and finally tensioned to fracture at room temperature. In addition, the remaining six pre-strained samples underwent annealing at 160 °C for 5 h and then experienced tensile testing at room temperature at an initial strain rate of 10^{-4} s^{-1}. The pre-stretching procedure introduced different characteristic substructure morphologies. The samples pre-stretched at liquid nitrogen and at room temperature were labelled PSL and PSR, respectively. The subsequent annealing treatment kept a significant lower temperature than for standard ageing treatments in the 6000 series alloys. As stated in a previous study on ultrafine-grained Al-Mg-Si alloys [20], the coherent precipitates β'' were stable at 160 °C and their morphology did not change significantly with increasing ageing time. In another work [21], it was evidenced that polycrystalline high purity aluminium subjected to a tensile pre-strain of 25% at room temperature, followed by annealing at 160 °C for 4 h, the dislocation density within sub grains was very low. Therefore, annealing at 160 °C for 5 h was adopted in the present work to reduce the dislocation density but without significantly changing the microstructure in terms of grain orientation and precipitate structures. The annealed specimens were referred to as "pre-stretching in liquid nitrogen and annealing" (PSLA) and "pre-stretching at room temperature and annealing" (PSRA), respectively. For more clarity of the experimental procedures, please refer to the flow illustration in Fig. 2.

An atomic force microscope (AFM, MultiMode 8) operated at room temperature in the contact mode facilitated three-dimensional (3D) surface topography information of pre-stretched specimens (PSL and PSR). These measurements were carried out on the plane defined by the extrusion - normal directions (see Fig. 1). Subsequently, EBSD